PROJECT CODE : SUT7-715-45-12-12

Research Report

Study of Temperature Distribution and Heat Generation in an Aerobic Composting Process Using Finite Difference Method

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Funded by Suranaree University of Technology 2002 Fiscal Budget

October 2002

บทคัดย่อ

การทำปุ๋ยหมักคือการทำของเสียให้เสถียรภาพที่ต้องการสภาวะแวดล้อมที่ดีที่สุดของอัตราส่วนคาร์บอนต่อไนโตรเจน, ความชื้น และการให้อากาศ เพื่อให้ผลเป็นอุณหภูมิเทอร์โมฟิลลิค ในการศึกษานี้ พลังงานความร้อนที่เกิดขึ้นและการกระจายตัวของอุณหภูมิในกระบวนการทำปุ๋ยหมักแบบให้อากาศของขยะอินทรีย์ได้ถูกนำมาวิเคราะห์ การศึกษาของกระบวนการมีพื้นฐาน มาจากการตรวจวัดอุณหภูมิที่เพิ่มขึ้นในกองปุ๋ยหมักกับอัตราการเป่าอากาศที่แตกต่างในถังปุ๋ยหมักทรงกระบอกสี่ใบ ขนาดเส้นผ่าศูนย์กลาง 0.5 ม. ยาว 1 ม. ขยะประเภทเศษอาหารเก็บมาจากตลาดสด ส่วนเศษขยะจากสนามหญ้า (เศษใบไม้และเศษหญ้า) เก็บมาจากบริเวณบ้านที่อยู่อาศัย ส่วนผสมของขยะมีอัตราส่วนคือ 1:0.03 โดยน้ำหนักสำหรับ เศษอาหาร : เศษหญ้า เพื่อให้ได้อัตราส่วนของคาร์บอนต่อไนโตรเจนเท่ากับ 20-30:1 การให้อากาศเป็นไปตามทางยาวของถังผ่านท่อพีวีซีขนาดเส้นผ่าศูนย์กลาง ½ นิ้ว อัตราการเป่าอากาศของการทดลอง RUN I, II, III และ IV คือ 1.8, 3.6, 5.4 และ 10 ลบ.ม./วัน ตามลำดับ อุณหภูมิในกองปุ๋ยหมักได้เพิ่มขึ้นอย่างรวดเร็วในช่วง 2-3 วันแรก อุณหภูมิสูงสุดพบว่าอยู่ที่จุดกึ่งกลางของกองปุ๋ย ผลคือ 64 °C, 51.8 °C, 55.4 °C และ 58.9°C ในวันที่ 15, 20, 10 และ 9 สำหรับการทดลอง RUN I, II, III และ IV ตามลำดับ อุณหภูมิจะถึงที่สภาวะเสถียรภาพหลังจาก 24-35 วัน ค่าการนำความร้อนที่ใช้ในการศึกษาได้มาจากการทดลองของตัวอย่างปุ๋ยต่าง ๆ และค่าเฉลี่ยคือ 0.53 วัตต์/ม./°C ค่าการกระจายความร้อนที่คำนวนได้คือ 2×10^{-7} ตร.ม./วินาที explicit finite difference method และสมการความร้อน 1 มิติ ของ Fourier ในแนวรัศมีของวงกลม เพื่อที่จะหาแบบแผนทางคณิตศาสตร์สำหรับโปรแกรมคอมพิวเตอร์ พลังงานความร้อนที่เกิดขึ้นต่อหนึ่งหน่วยปริมาตร (วัตต์/ลบ.ม.) ได้ถูกประมาณคือ 133, 221.4, 242 และ 483.7 วัตต์/ลบ.ม. สำหรับการทดลอง RUN I, II, III และ IV ตามลำดับ ผลการศึกษาบ่งชี้ว่าการกระจายตัวของอุณหภูมิและพลังงานความร้อนที่เกิดขึ้นระหว่างกระบวนการทำปุ๋ยหมักแบบใช้อากาศนั้น มีผลกระทบจากอัตราการเป่าอากาศ

ABSTRACT

Composting is a waste stabilization process that requires optimum operating conditions of C/N ratio, moisture, and aeration to achieve thermophilic-temperatures. In this study, heat generation and temperature distribution during the in-vessel aerobic composting of organic fractions of municipal solid waste were investigated. The process evaluations were based on monitoring temperature rise in composting mass with different aeration rates. Four insulated cylindrical composters made of zinc sheets with 0.5 m diameter and 1 m length were used. Food waste collected from fresh food market and household yard waste were mixed at a ratio of 1:0.03 by weight to obtain a C/N ratio of 20-30:1. Air was supplied length-wise to the central axis of the composters through ½" PVC pipes. Aeration rate provided for four experimental runs, RUN I, II, III and IV were 1.8, 3.6, 5.4 and 10 m^3/d, respectively. Rapid temperature rise during composting runs was found within the fist few days (1-3 days). The maximum temperatures detected at the center of the composting mass, were 64 °C, 51.8 °C, 55.4 °C and 58.9°C on the 15th, 20th, 10th, and 9th day of RUN I, II, III and IV, respectively. The temperatures were stabilized (ambient temperature) after about 24-35 days. Thermal conductivity of the composted material was experimentally determined on the samples from different runs and the average was 0.53 W/m/°C. The thermal diffusivity was calculated to be 2×10^{-7} m^2/s. A numerical scheme was developed by using explicit finite difference method with one-dimensional Fourier's heat equation along radial directions. Using the numerical scheme, heat generated per unit volume during each run were obtained to be 133, 221.4, 242 and 483.7 W/m^3 for RUN I, II, III and IV, respectively. The results indicated that temperature profiles and heat generation during the aerobic composting process were influenced by aeration rates.

ACKNOWLEDGEMENTS

The principle investigator of this study wishes to express acknowledgement to the Research Institute, Institute of Engineering, Suranaree University of Technology and the National Research Council of Thailand (NRCT) for providing the necessary funding to conduct this research.

The greatful recognition is due for Prof. Dr. Vinod K. Jindal who had given his advices in mathematical modeling, numerical scheme and computer program.

Finally, her research assistants, Putong Ratanamalaya, Pramote Kongsaktrakul and Supakinha Somsri, deserve thanks for their help and assistant during the course of this project.

Ranjna Jindal

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List of Symbols and Abbreviations

α = Thermal diffusivity constant

A = The area of cross section through which heat flows

c = Specific heat capacity by means of heat required to rise the temperature of unit mass (1 g) by 1 °C

$C_aH_bO_cN_d$ = Organic matters

C/N = Carbon to nitrogen ratio

CO_2 = Carbon dioxide

°C = Degree Celsius

d = Diameter

ΔE = Change in internal energy of the system

°F = Degree Fahrenheit

h = Heat

h = Convection heat transfer coefficient

H_2O = Moisture, water

I = Current

k = Thermal conductivity of the medium

l = Length

m = Mass

N = Number of grids

n = Unit number

NH_3 = Ammonia

O_2 = Oxygen

q = Heat flow in the system

q_x = The rate at which heat enters the face located at x

q_V = heat flow in the system maintained at constant volume

$\overset{\circ}{q}$ = The heat generation per unit volume

Q_{air} = Air flow rate

r = Distance r

List of Symbols and Abbreviations (cont.)

R = Radius

RQ = The respiratory quoteint

SO_4^{2-} = Sulfate

t = Time

T = Temperature

T_s = Surface temperature

T_∞ = Ambient fluid temperature

$\frac{\partial T}{\partial x}$ = Temperature gradient

TS = Total solids

TVS = Total volatile solids

V = Volume

V = Voltage

W = watt

CHAPTER I

always happen, and that the remaining stable organic fraction is useful to soils and plants, is one of the reasons composting has such value.

There are several benefits of composting. It is a great recycler; it is more than a fertilizer, more than a soil conditioner; it provides and releases plant nutrients, projects against drought and stops nutrient loss through leaching. It builds good soil texture and structure, stops erosion and improves aeration. Compost products can alter acidity or alkalinity and also can stimulate plants growth (Devkota, 1984).

There are two types of composting based on oxygen frequirements, namely, aerobic composting and anerobic composting. Aerobic composting is the decomposition of organic substrates in the presence of oxygen (air), while anaerobic composting process undergoes without air. Unlike aenarobic composting, aerobic composting generates significantly higher amount of heat from decomposition of organic materials.

Composting process is currently viewed primarily as a waste management method to stabilize organic waste, such as manure, yard trimmings, municipal biosolids, and organic urban wastes. The stabilized end-product (compost) is widely used as a soil amendment to improve soil structure, provide plant nutrients, and facilitate the revegetation of disturbed or eroded soil (U.S.EPA, 1998). This process can be carried out on a large or small scale, with the management of optimum operating conditions.

In its simplest form, compostable material is arranged in long rows (windrows) and turned periodically to ensure good mixing. This process can handle large quantities of input, such as yard trimmings of up to 100,000 cubic yards per year, on only a few acres of land. Raw materials that tend to be very odorous during composting, such as municipal waste sludge (biosolids), can be processed in more elaborate systems and in a confined facility where odorous air can be treated. These systems use rotating drums, trenches, or enclosed tunnels for initial processing, followed by a covered curing period (U.S.EPA, 1998).

All composting methods share similar characteristic features and processes. Initially high microbial activity and heat production cause temperatures within the compostable material to rise rapidly into the thermophilic range (50 ^{o}C and higher). This temperature range is maintained by periodic turning or the use of controlled air flow. After the rapidly degradable components are consumed, temperatures gradually fall during the "curing" stage. At the end of this stage, the material is no longer self-heating, and the finished compost is ready for use. Substantial changes occur in microbial populations and species abundance during the various temperature stages.

Mesophilic bacteria and fungi are dominant in the initial warming period, thermophilic bacteria (especially actinomycetes) during the high temperature phase, and mesophilic bacteria and fungi during the curing phase (U.S.EPA, 1998).

1.2 Statement of the Problem

Maintaining thermophilic temperatures is a primary requirement for pathogen inactivation and seed destruction. When the temperatures exceed an organisms' optimal growth temperature, the organisms quickly come under severe stress. Temperatures slightly below the optimum can generally be tolerated better then temperatures slightly above the optimum (Anonymous, 1986). Thus, composting process requires special conditions of moisture and aeration to acheive thermophilic temperature. Such biological stabilization and conversion processes deal with dilute aqueous solutions, and only limited temperature evaluations are possible (Haug, 1993).

The basic objective of process control objective is to maximize microbial activity at the expense of the organic waste being treated. This is equivalent to maximizing metabolic heat output. In a self-heating ecosystem, temperature is both effect and cause. It is a function of the accumulation of heat generated metabolically, and simultaneously, temperature is a determinant of metabolic activity. The correlation between heat output and temperature is the centerpiece of rational control of the composting process (MacGregor, Miller, Psarianos, and Finstein, 1981).

Heat evolution, occurring in proportion with microbial metabolic, is a fundamental means of observing the rate of composting activity in situ. The effect of various parameters on microbial activity can be quantified through monitoring the metabolic heat generation. In design and management of composting systems, heat management is the basis of temperature control (Miller, 1996). While the effect of temperature on composting is well understood, the kinetics and thermodynamics of heat evolution during the process are not fully investigated. It is worthy of investigation for both scientific and engineering reasons. Therefore, the relationship between heat generated and temperature distribution in forced aeration composting process should be studied. In addition, understanding the process maturation and stability of the remaining fraction is therefore of great significance (Brinton, Evans, Droffner, and Brintrin, 1995).

1.3 Research Objectives

The overall aim of this study was to investigate the heat generation during an aerobic composting process, specific objectives included the following:

1.3.1 to investigate the temperature rise in aerobic composting of organic fractions of municipal solid wastes

1.3.2 to develop a numerical scheme for obtaining heat generation from temperature profiles

1.3.3 to estimate the heat generation from the experimental temperature profiles utilizing the developed numerical scheme

1.3.4 to evaluate the influence of air flow rate on heat generation and temperature profiles

1.4 Scope and Limitations of the Study

To accomplish the above objectives following tasks were covered in the scope of this study:

1.4.1 modified insulated cylindrical composters were used for this study

1.4.2 aerobic composting process was carried out with the mixture of food waste collected from fresh food market and household yard waste

1.4.3 chemical and physical characteristics determined for the composting mass constituents included: total solids (TS), moisture contents, volatile solids (VS), ash, carbon (C), nitrogen (N), C/N ratio, pH, thermal conductivity, and thermal diffusivity

1.4.4 experimental runs with different aeration rates were conducted

1.4.5 the numerical scheme was developed for heat generation in the composting mass

1.4.6 only one-dimensional relationship between the heat generation ($\overset{\circ}{q}$) and the temperature distribution ($\frac{\partial T}{\partial t}, \frac{\partial T}{\partial r}$) along radial direction was considered

CHAPTER II

COMPOSTING

2.1 Composting

Composting process is currently viewed primarily as a waste management method to stabilize organic waste, such as manure, yard trimmings, municipal biosolids, and organic urban wastes. The stabilized end-product (compost) is widely used as a soil amendment to improve soil structure, provide plant nutrients, and facilitate the revegetation of disturbed or eroded soil (U.S.EPA, 1998). This process can be carried out on a large or small scale, with the management of optimum operating conditions.

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Aerobic composting process can be represented by following biochemical reaction (Tchobanoglous, Theisen, and Vigil, 1993):

$$\begin{matrix}\text{organic}\\ \text{matter}\end{matrix} + O_2 + \text{Nutrients} \xrightarrow{\text{microorgan isms}} \begin{matrix}\text{new}\\ \text{cells}\end{matrix} + \begin{matrix}\text{resistance}\\ \text{organic}\\ \text{matters}\end{matrix} + CO_2 + H_2O$$

$$+ NH_3 + SO_4^{2-} + \ldots + \text{heat} \qquad (2.1)$$

With empirical formula for mole composition of the organic material initially present in a composting pile and for complete conversion, the oxygen requirement may be calculated by the following equation (Tchobanoglous *et al.*, 1993):

$$C_aH_bO_cN_d + \frac{4a + b - 2c + 3d}{4} O_2 \rightarrow aCO_2 + \frac{b - 3d}{2} H_2O + dNH_3 \qquad (2\text{-}2)$$

It can be seen from equations (2.1) and (2.2) that aerobic degradation requires

(a) oxygen,

(b) nutrients, and

(c) microorganisms.

The end products of composting process include:

(a) compost,

(b) gases,

(c) moisture, and

(d) energy.

According to Stentiford (1996), there are three principal factors to control during aerobic composting process, namely

(a) aeration

(b) temperature and

(c) moisture content.

The air could be supplied to a composting process by

(a) agitation, i.e., windrow composting,

(b) forced aeration, i.e., aerated static pile composting, and

(c) combination of agitation and forced aeration.

The required air flow rate could be controlled and monitored in the laboratory using appropriate instruments. The oxygen requirement depends on

(a) type of waste (nutrients, particle size, etc.),

(b) process temperature,

(c) stage of the process (higher requirements in the early stages), and

(d) process conditions (moisture content, structures, etc.).

The environmental temperature has an important effect on the survival and growth of microorganisms. Tchobanoglous *et al.*, (1993) and Miller, (1991) defined temperature ranges for microbial growth and survival as shown in Table 2.1.

Table 2.1 Typical temperature ranges for various bacteria

Type	Temperature					
	Tchobanoglous, 1993				Miller, 1991	
	°C		°F		°C	°F
	Range	Optimum	Range	Optimum		
Psychophilic	-10-30	15	40-110	85	< 20	< 94
Mesophilic	20-50	35	94-150	120	> 40	>130
Thermophilic	45-75	55	140-193	157	> 45	>140

In general, U.S.EPA Part 503 rule for composting requires pathogens and vector attraction reduction (Switzenbaum *et al.*, 1997). The physical stability of the end product of composting which is important for transporting, handling, storage and application, is assesed by:

(a) stabilized temperature/heat output,

(b) color,

(c) odor, and

(d) solid destruction.

There are various procedures recommended for compost stability assessment, both by direct and indirect measurement. Their assessment must be made based on the energy available for biological oxidation.

In order to control the composting process, microbially generated heat must be removed from a mass body. This is to prevent the temperature of the substrate, which is a good thermal insulator, from reaching levels inhibitive to the resident microbial population. The heat transfer mechanisms involved are convection and conduction, with radiation effects being assumed negligible (Shaw and Stentiford, 1996).

Aeration rate and temperature profiles are the principal variables to be monitored during the composting process, with air supplied by agitation, forced aeration, or combination of both. The disadvantage of agitation or windrow composting is that the temperature of the mass is never properly controlled, leaving unavailability in allowance of optimum temperature condition for biodegradation. Whereas, static pile composting has major disadvantage in the inability to readily change the physical conditions within the pile mass. A very typical problem is the occurrence of excessive drying which influences process inhibition due to dryness. The combination of agitation and forced aeration absolutely overcomed both problems but that it also causes an increase in capital investment. Admittedly, there are alternatives for controlling aerobic composting, though, reactor based systems seemed to be adequate for all small-scale studies.

Leton and Stentiford (1990) studied the relationships between composting parameters related to aeration rates provided to a static composting pile. They had reached a conclusion that only the automated aeration system could actually cater for the dynamic nature of the composting process. Advantages such as a means of monitoring aeration effectiveness, and an indication of the end of active composting could be incorporated into the system. The forced aeration method of static pile composting was claimed to enhance the process, and the active decomposition period could be cut down from 40 days or more in the windrow system to about 21 days in the static pile system. This reduction in active composting time (the period from the time the pile is built to when it is taken off the aeration pad) was not solely a feature of the aeration method but depended on a number of other interactive factors. These factors were: nature of raw material, mixing ratio (C/N ratio), moisture content, particle size, and temperature within the compost mass. Serveral programs were designed for an automation of aeration rates. An automated rate of aeration control was determined from the feedback of information on oxygen and/or temperature levels in the pile.

In another study (Stentiford, 1996), in order to develop a mathematical model for relationship between heat generation and temperature distribution of a composting system, forced aeration was utilized as a control variable. Air was supplied to the composting mass by a pressurized system, typically low head (below 150 mm) high volume fan units. Three possible methods were employed:

(a) blowing air into mass, positive pressure

(b) sucking air through the mass, negative pressure

(c) hybrid (combination of both), this method could give greater flexibility in operation.

The forced aeration was controlled to distribute the air throughout the mass. The positive pressure seemed to be the best methodology because, it was easy to provide and properly control the aeration rate. Although, the reactor-based systems were rather large but small bench-scale and pilot-scale were often utilized for research.

2.2 Heat Generation and Temperature Distribution

Figure 2.1 shows the typical temperature/time profiles for different composting systems. This figure shows that the temperature will rapidly increase for the first composting stage and reach the optimum temperature within 7 days. Then sanitisation occurs during the optimum temperature period. As the temperature decreases, the biodegradation takes place for certain period of time and finally cooling stage.

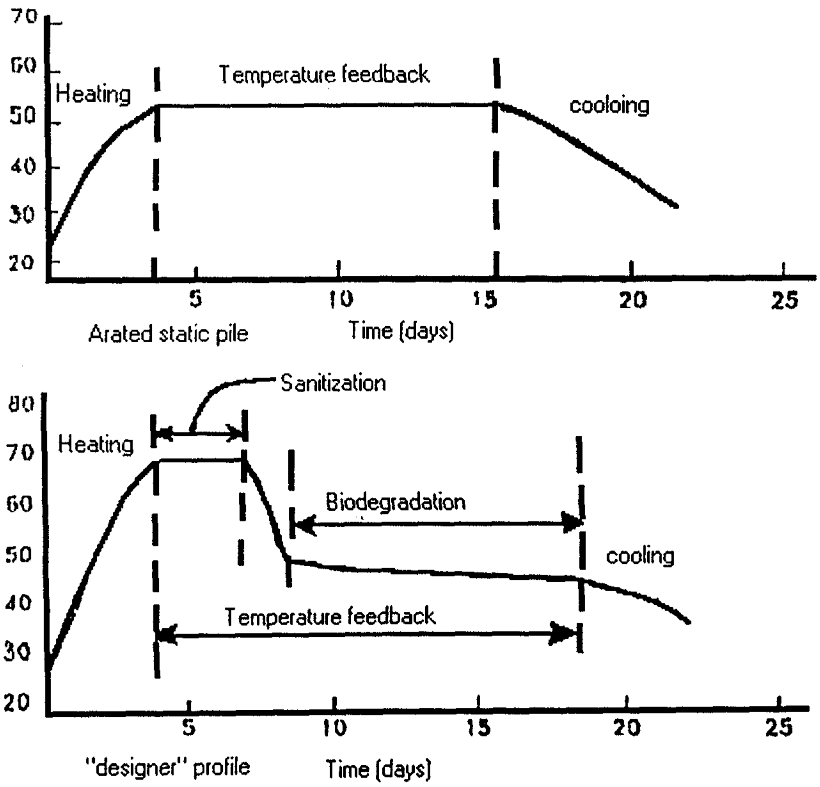


Figure 2.1 Typical Temperature/time profiles for different compost systems

(source: Stentiford, 1996)

CHAPTER III

NUMERICAL SCHEME

3.1 Thermodynamics

Thermodynamics is normally associated with heat, but the subject deals not only with heat but all forms of energy. Application of thermodynamic principles is a fundamental way of analyzing composting systems. The first law of thermodynamics, for any system maintained at constant volume (isovolumetric) is generally presented as follows (Haug, 1993):

$$q_V = \Delta E \qquad (3.1)$$

where,

q_V = heat flow in the system maintained at constant volume

ΔE = change in internal energy of the system

The heat per unit mass flowing into a substance (dq) can be defined as:

$$dq = mcdT \qquad (3.2)$$

where,

c = the specific heat capacity

m = the mass

dT = the temperature change

Integrating equation (2.4), $q = m\int_{T_1}^{T_2} cdT$

Assuming a constant-volume process with constant specific heat, integration gives

$$q_V = mc\Delta T \qquad (\Delta T \text{ not large}) \qquad (3.3)$$

3.2 Numerical Scheme

A mathematical model of any physical system is a prediction device, which represents the full-sized phenomenon at a small scale. The models are intended to reproduce physical, chemical and biological reactions. If the equations depicting the physical events are known in sufficient detail, they can be useful in developing the design criteria of the real system without great difficulty (Jindal, 1995.) Many mathematical models have been investigated to describe the composting process. Unfortunately, there have not been many studies and reports on heat flow in composting systems. Such study will be useful for the improvement and control of forced aeration in composting procedures.

Theoretically, heat is the energy exchange between temperature differences, generally, from higher to lower temperature. Heat transfer is a study of how fast the energy is exchanged as heat. Three equations that have been used to describe the various modes of heat transfer are conduction, convection, and radiation (Rolle, 2000)

Conduction heat transfer is the normal transfer of energy within solids. It may also occur in gases and liquids, if they are stagnant or move slowly. Materials that conduct heat well, or rapidly, are called conductors and have high values of thermal conductivity. The mathematical equation for conduction heat transfer is Fourier's Law of Conduction:

$$q = -kA\frac{\partial T}{\partial x} \tag{3.4}$$

where, q is the heat transfer in the x direction crossing the normal area A due to the temperature gradient $\frac{\partial T}{\partial x}$ (Rolle, 2000).

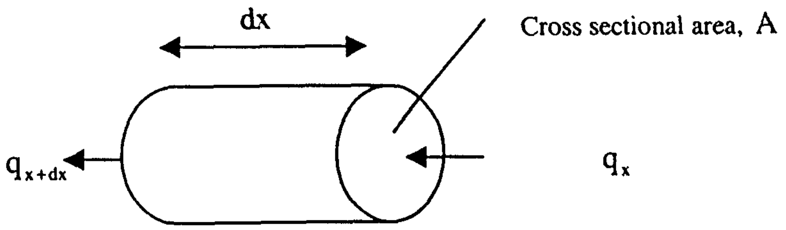
Convection heat transfer is the mode of energy exchange that is associated with heat crossing a boundary or surface between a solid and a fluid. It is a macroscopic phenomenon and, when considered in detail, the model does not satisfy the thermodynamic definition of heat transfer. It is a model that is used with the idea of a boundary layer of a fluid at a solid surface so that there can be heat flow to (or from) the bulk fluid around the solid. The mathematical equation for convection heat transfer is expressed by Newton's Law of cooling as shown below:

$$q = hA(T_s - T_\infty) = hA\Delta T \tag{3.5}$$

where, T_s is the surface temperature, T_∞ is the ambient fluid temperature, and h is the convection heat transfer coefficient (Rolle, 2000).

The third model describing heat transfer between systems is radiation. This model is used for explaining observations of energy traveling through a distance without seeming to involve the intermediate volume (Rolle, 2000).

Consider a small element of material in a solid body as shown in the figure below.



The energy balance equation can be stated as follows (Rao, 1999):

$$\begin{matrix}\text{Heat}\\ \text{inflow}\\ \text{during}\\ \text{time dt}\end{matrix} + \begin{matrix}\text{Heat generated by}\\ \text{internal sources}\\ \text{during dt}\end{matrix} = \begin{matrix}\text{Heat}\\ \text{outflow}\\ \text{during dt}\end{matrix} + \begin{matrix}\text{Change in}\\ \text{internal}\\ \text{energy}\\ \text{during dt}\end{matrix}$$

With the rate expressions, this equation can be written as

$$q_x dt + \overset{\circ}{q}\, dxdt = q_{x+dx} dt + \rho c dT dx \tag{3.6}$$

where

$q_x = -kA\frac{\partial T}{\partial x}$ = the rate at which heat enters the face located at x

$q_{x+dx} = -kA\frac{\partial T}{\partial x} - \frac{\partial}{\partial x}\left(kA\frac{\partial T}{\partial x}\right)dx$

= heat outflow rate from the face located at $x + dx$

$\overset{\circ}{q}$ = rate of heat generated per unit volume (per unit time)

k = the thermal conductivity of material

A = the area of cross section through which heat flows

$\frac{\partial T}{\partial x}$ = the rate of change of temperature, T with respect to the axial direction, x

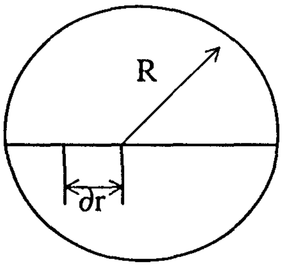
Dividing each term by dx, we obtain

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \overset{\circ}{q} = \rho c\frac{\partial T}{\partial t} \tag{3.7}$$

If a constant $\alpha = \frac{k}{c\rho}$, then

$$\frac{\partial^2 T}{\partial x^2} + \frac{\overset{\circ}{q}}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{3.8}$$

If cylindrical coordinate system is used instead of the cartesian system and $\frac{\partial^2 T}{\partial x^2} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)$, then equation (3.8) becomes



$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\overset{\circ}{q}}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{3.9}$$

where,

T = temperature, ^{o}C

r = distance along radial direction, m

$\overset{o}{q}$ = the rate of heat generation per unit volume (by heat source), W/m^3 or $J/s/m^3$

k = thermal conductivity of the medium, $W/m/^{o}C$

α = thermal diffusitivity constant, m^2/s

ρ = bulk density = the mass per unit bulk volume, kg/m^3

t = time

Heat transfer is used for explaining and predicting many physical processes. The subject can be rationally approached if we reflect on the types of problems and solution to be encountered. In heat transfer, there are essentially two classes of problems (Rolle, 2000).

1) Given a temperature distribution, determine the heat transfer.
2) Given a rate of heat transfer, determine the expected temperature distribution.

Numerical schemes commonly used to solve the heat equation include the finite-difference method, the finite-element method, and the boundary-element method. Finite-different method is commonly used to solve unsteady one-dimensional heat transfer equations. It was the first numerical method to be used extensively for heat conduction. This method remains popular, not because it is superior to other methods for heat conduction, but because it is easier to implement and is also the most useful numerical scheme for heat convection problems (Mills, 1999).

The finite-difference solution for differential equations in mathematical-physics is carried out in two stages:

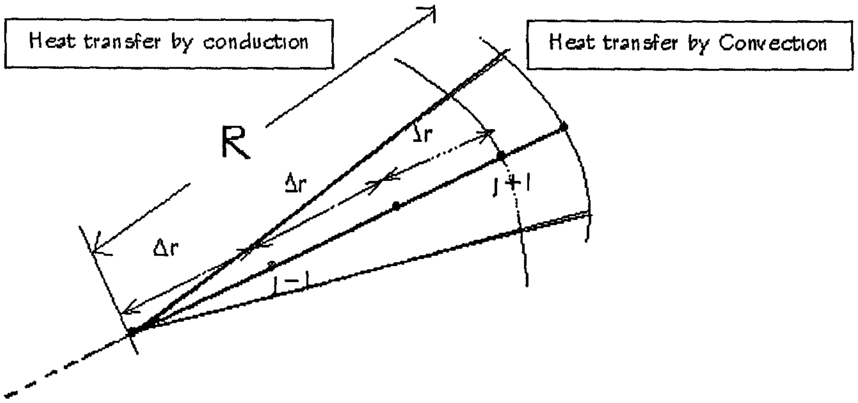
a) the writing of the finite-difference scheme (a difference approximation to the differential equation on a grid).
b) the computer solution for difference equations, which is written in the form of a high-order system of linear or non-linear algebraic equations.

The essence of the method of finite difference is as follows:

a) The continuous domain is replaced by a discrete set of points, called grid.
b) Instead of a function of continuous arguments, a function of discrete argument is considered. The value of this function is defined at the nodes of the grid or at other elements of the grid and is called the grid function.
c) The derivatives entering into the differential equations and the boundary conditions are approximated by the difference expression, thus the differential problem is

transformed into a system of linear or non-linear algebraic equations. Such a system is often called the finite-difference scheme (Shashkov, 1996).

The first step in a finite-difference solution scheme was to discretize the spatial and time coordinates to form a mesh of nodes. Consider radial heat transfer in a long, solid cylinder of radius r = R in which heat is generated as $\overset{\circ}{q}(r)$ W/m^3. The region $0 \le r \le R$ may be divided into N cylindrical subregions, each of thickness $\Delta r = \frac{R}{N}$ as shown below.



Next, finite-difference approximations were made to derivatives appearing in the heat equation (Chapter 2) to convert the differential equation to an algebraic difference equation. Alternatively, the difference equation can be constructed by applying the energy conservation principle directly to a volume element surrounding the node. For transient conditions, temperatures at the current time step may be found directly using values at the preceding time step. Accuracy of a finite-difference approximation increases with number of nodes (Mills, 1999).

Explicit form of finite-difference approximations for one-dimensional unsteady conditions was used. Therefore, equation (3.9),

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\overset{\circ}{q}}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

was substituted with,

$$\frac{\partial^2 T}{\partial r^2} = \frac{1}{(\Delta r)^2}\left[T_{i-1}^{p} + T_{i+1}^{p} - 2T_i^{p}\right]$$

$$\frac{\partial T}{\partial r} = \frac{T_{i+1}^{p} - T_{i-1}^{p}}{2(\Delta r)}$$

$$\frac{\partial T}{\partial t} = \frac{T_i^{p+1} - T_i^p}{\Delta t}$$

Where, i or j = nodal positions

p = time steps

T_i^p = temperature of point i at time p

T_{i-1}^p = temperature of point i-1 at time p

T_{i+1}^p = temperature of point i+1 at time p

T_i^{p+1} = temperature of point i at time p+1

Δt = time step (duration between time p and p+1)

As a result, the *finite-difference form* (Özişik, 1985) of heat equation can be written as:

$$\frac{1}{(\Delta r)^2}\left[T_{i-1}^p + T_{i+1}^p - 2T_i^p\right] + \frac{1}{r}\left[\frac{T_{i+1}^p - T_{i-1}^p}{2(\Delta r)}\right] + \frac{\overset{\circ}{q}}{k} = \frac{1}{\alpha}\left[\frac{T_i^{p+1} - T_i^p}{\Delta t}\right] \tag{3.10}$$

In order to solve the heat equation, boundary and initial conditions were used to evaluate integration constants. In well-insulated system, heat flux at the boundary is simply known (assumed) to be zero. Transient heat problems usually require specification of an initial condition, which simply means that the temperature throughout the mass body must be known at an instant of time before its subsequent variation with time can be determined (Mills, 1999). For this study, uniform initial temperatures throughout the mass were taken to be known, thus, $T_{i-1} = T_i = T_{i+1}$.

Let $m = \frac{\alpha \Delta t}{(\Delta r)^2}$, and Fourier Number, which is a dimensionless time variable, $\frac{\alpha t}{L^2}$ = 0.25 = $\frac{\alpha \Delta t}{(\Delta r)^2}$, thus, $\Delta t = \frac{0.25(\Delta r)^2}{\alpha}$. In addition, h = heat transfer coefficient (specific conductivity) and T_∞ = ambient temperature. These values were utilized as follows:

Equation for interior nodes:

$$T_i^{p+1} = \frac{m}{2}\left[\left(2 + \frac{\Delta r}{r_i}\right)T_{i+1}^p + \left(2 - \frac{\Delta r}{r_i}\right)T_{i-1}^p + \left(\frac{2}{m} - 4\right)T_i^p + \left(\frac{2(\Delta r)^2 \overset{\circ}{q}}{k}\right)\right] \tag{3.11}$$

Equation for center node: At the center, $r = 0$ and $T_{i-1} = T_{i+1}$. After some rearrangement of the terms, equation (3.10) yields

$$T_i^{p+1} = 4mT_{i+1}^p + \left(1 - 4mT_i^p\right) + \left(\frac{m(\Delta r)^2 \overset{\circ}{q}}{k}\right) \tag{3.12}$$

Equation for surface node: Equation for node N on the surface was determined by applying $T_i = \dfrac{T_{i-1} + \dfrac{h\Delta r}{k} T_\infty}{1 + \dfrac{h\Delta r}{k}}$ at the boundary and by taking into a consideration the boundary condition.

After the rearrangement of the terms,

$$T_N^{p+1} = \frac{T_{N-1}^{p+1} + \dfrac{h\Delta r T_\infty}{k} + \dfrac{1}{2}\dfrac{(\Delta r)^2 h \overset{\circ}{q}}{k}}{1 + \dfrac{h\Delta r}{k}} \tag{3.13}$$

Equations (3.10)-(3.13) were used in a computer program to simulate the temperature distribution of the composting mass during the biodegradation process of each run. The computer program is shown in Appendix G. Heat generated per unit volume, $\overset{\circ}{q}$, were assumed for each simulation run, and the rates of temperature change with time, $\dfrac{\partial T}{\partial t}$, were compared with the experimental ones.

CHAPTER IV

METHODOLOGY

4.1 Research Procedure

The overall procedure involved, collection of the waste materials, obtaining the appropriate mixture for the aerobic process, and recording the temperatures of the composting mass as the biodegradation took place. Figure 3.1 shows the overview of the complete procedure.

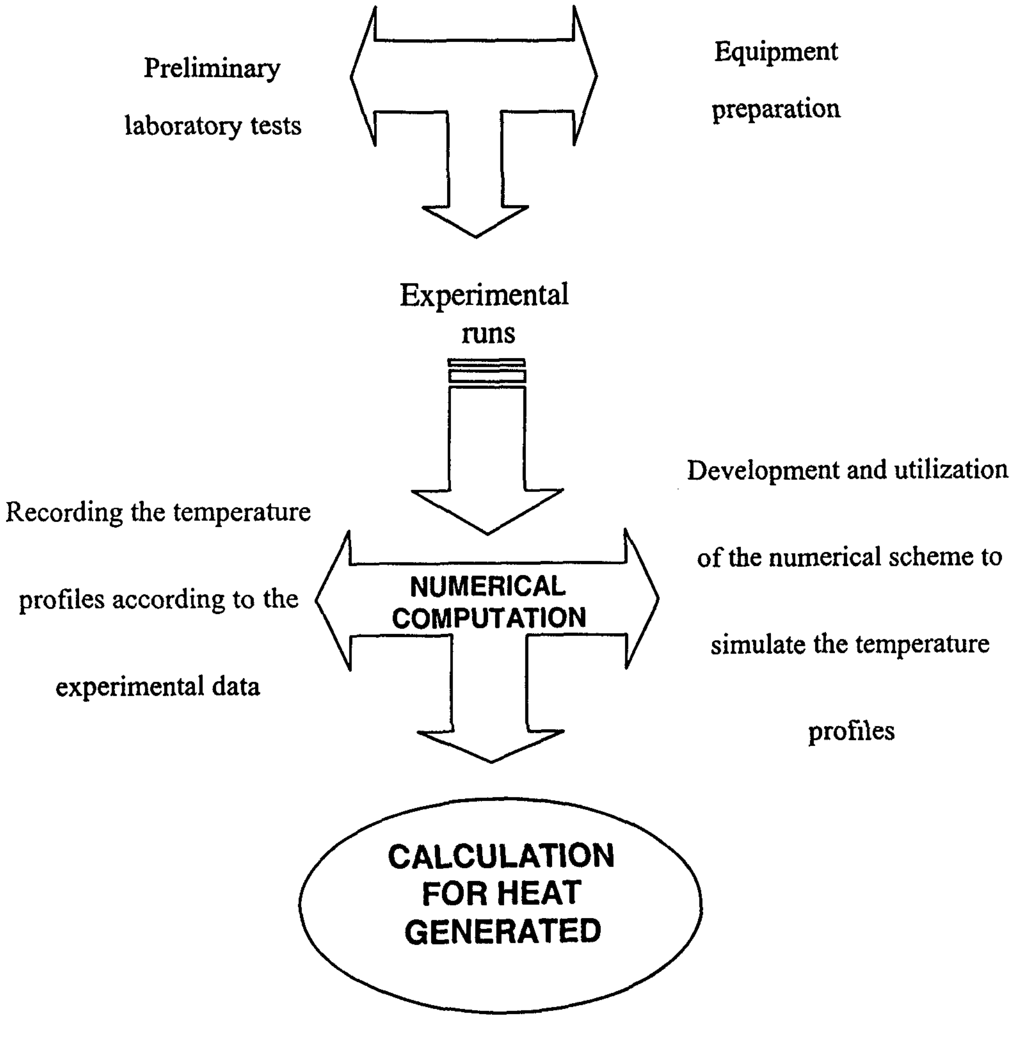
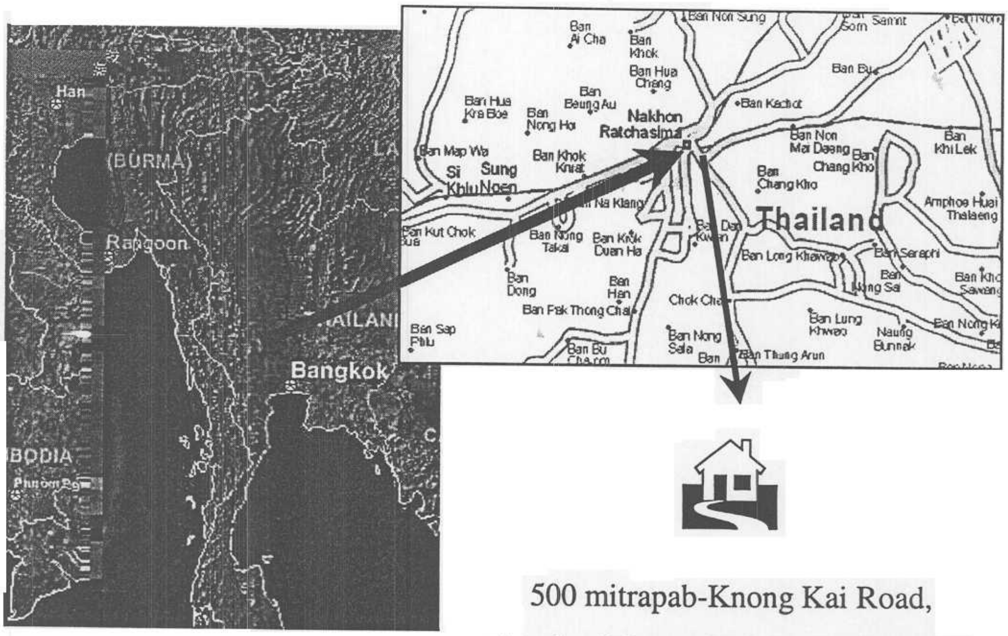


Figure 4.1 Schematic diagram of research procedure

4.2 Experimental Location

Experimental site of this study was at a house (Suntudtong residence) located at kilometer 7 on Mittrapab-Knong Kai road, Nakhon Ratchasima, which is in the Northeastern region of Thailand. Figure 4.2 shows the experimental location.



500 mitrapab-Knong Kai Road,
Ampher Maung, Nakhon Ratchasima

Figure 4.2 Experimental location

4.3 Experimental Setup

a) Composters: Four cylindrical composters made of zinc sheet, insulated with microfiber, with dimensions: length (l) of 1.0 m, diameter (d) of 0.5 m, and volume $(\forall)$ of approximately 0.196 m^3, were used for the pilot-scale experiments of this study.

b) Thermocouples: Type K thermocouples were inserted at different positions in each reactor for temperature measurement.

c) Air diffusers: $\frac{1}{2}''$ PVC pipes with $\frac{1}{8}''$ holes in all directions were inserted in the center of each composter.

d) Aeration: An air compressor was used to supply air to all composter.

e) Air flow meter: A flow meter was installed to monitor aeration rate provided to the composters.

f) Data loggers: Data loggers and a computer were used to monitor time and temperatures. The complete setup is shown in the following figure.

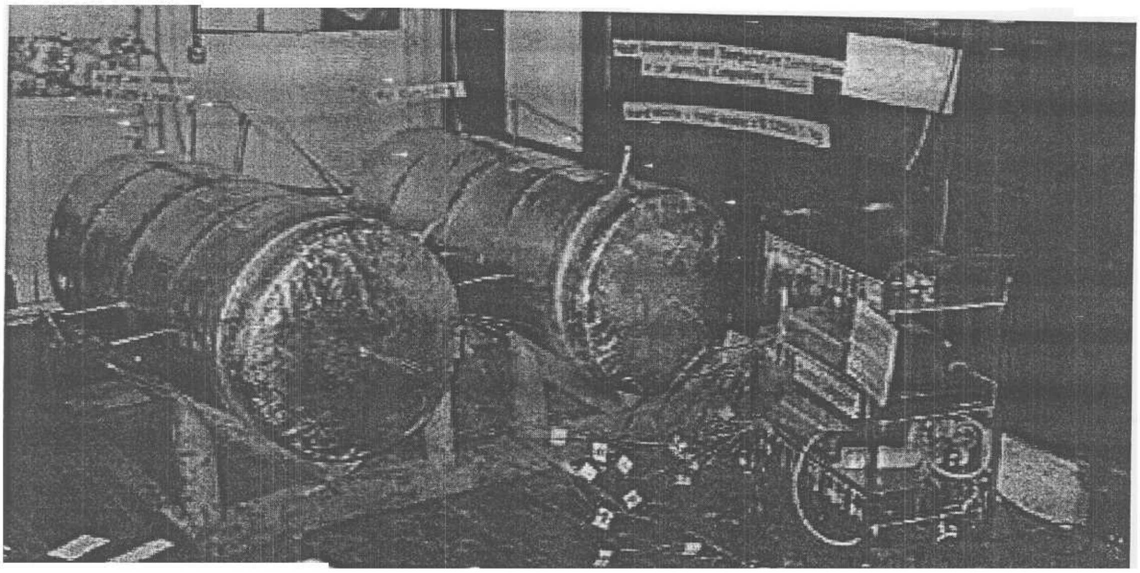


Figure 4.3 Experimental setup

4.4 Composting Materials

Mixture of two different organic waste materials was used to conduct the composting experiments for this study. The organic waste components were yard waste and food waste. Yard waste consisted of grass trimmings and fallen leaves. Food waste consisted of household kitchen waste mixed with vegetable and fruit trimmings. Sources of the waste materials for the experiments are briefly described as follows:

a) Grass trimming and fallen leaves were collected from Suntudtong Farm on Mittrapab-Paktongchai road, in front of the Suranaree University of Technology main entrance.

b) Food waste was be collected from Korat City neighborhood household trash bins mixed with Sura Nakhon market (Nakhon Ratchasima) vegetable and fruit trimming waste.

4.5 Preparation of Composting Mixture

Waste samples of all fractions were analyzed in the laboratory for the determinations of: bulk density, moisture content, total solids (TS), total volatile solids (TVS), organic carbon, total organic nitrogen, and C/N ratio. The composting material mixture ratio was calculated from the preliminary laboratory analyses (Appendix B). The aeration requirements were estimated following the examples of some previous studies as shown in Appendix C.

The waste samples were chopped and cut as recommended by Tchobanoglous, et al., 1993; for optimum results, the size of solid waste should be between 25 and 27 mm (1 and 3 in.). Food waste and yard waste mixture (weight basis ratio) was placed in the composters for each composting run.

4.6 Composting Runs

Four experimental RUN I, II, III, and IV, were conducted with different aeration rates provided for each composting process. Table 4.1 shows the experimental plan of this study. Time and temperature were recorded hourly. Experimental results were analyzed with the developed numerical scheme.

Table 4.1 Duration and airflow rates of four composting runs

Experimental run	Aeration rate Q_{air}	Number of days run
RUN I	1.25 L/min (1.8 m^3/day)	85 days
RUN II	2.50 L/min (3.6 m^3/day)	45 days
RUN III	3.75 L/min (5.4 m^3/day)	85 days
RUN IV	7.50 L/min (10 m^3/day)	49 days

4.7 Thermal Properties of Composting Materials

Thermal conductivity (k): The thermal conductivity, k, of solids and liquids is considered to be constant and usually expressed in units of cal/(h-cm^2-°C/cm) or Btu/(h-ft^2-°F/ft). Theoretically, heat conducts from the center of heat source through the media. If the media (composting material) has poor thermal conductivity, the temperature rises faster at the center of heat source. Values of k between 2 and 4 cal/(h-cm^2-°C/cm) have been measured for different compost materials (Haug, 1993). The basic equation used for calculation of thermal conductivity (Prajaubwan, 2000) is given as below:

$$T = \frac{q}{4\pi k} \ln t \qquad (4.1)$$

Where,

T = temperature

q = heat applied to the heat source

t = time

k = thermal conductivity

Thermal conductivity measurement involves a heat source (thermal conductivity probe) provided with a known constant current and voltage. The temperature and time are measured and recorded by type T thermocouples and the data logger, respectively. Thermal conductivity (k) may be determined from the slope (m) of the straight line resulting from the semi-logarithmic plot of time (t) versus temperature (T). The thermal conductivity measurement was conducted in a laboratory at the Asian Institute of Technology (AIT), in Pathumthani province of Thailand.

Power input to a heat source of length, L, may be expressed as follow:

$$P = \frac{IV}{L} \tag{4.2}$$

where,

P = power supplied to the heat source, W/m

L = effective length of the heat source, m

I = current, amp

V = voltage, volts

Heat applied to the media is given by the following equation

$$q = \frac{IV}{4\pi kL} \tag{4.3}$$

Agar gel was used to calibrate this setup. Four samples of composted materials of different time-durations, and so, having different moisture contents, were used to obtain average thermal conductivity of the composting end product.

Thermal diffusivity (α): Thermal diffusivity could be calculated from the relationship, $\alpha = \frac{k}{\rho c}$. The thermal conductivity (k) was obtained from the above experiment, specific heat capacity (c) of the compost material was taken from some previous study and density (ρ) of the compost material mixture was measured in the laboratory.

Heat generation ($\overset{\circ}{q}$): A computer program was used to create the simulated temperature profiles for each experimental runs' conditions, i.e., initial temperature, ambient temperature, etc. Heat generated for each time-period was assumed in the program. The temperature outputs of the simulated profiles were compared with the experimental profiles to obtain heat generation.

CHAPTER V

RESULTS AND DISCUSSION

5.1 Characteristics of Composting Mixture and End Products

The results of the laboratory analyses of the composting mixture and the end products during the four experimental runs are shown in Table 5.1.

Table 5.1 Initial and final characteristics of composting mixture for each experimental run

Sample	% Moisture	% Solids	% VS	% ash	% C	% N	C/N Ratio	pH
Run I-initial	77.93	22.07	83.13	16.87	40.09	1.49	27.13	5.50
Run I-final	72.74	27.26	50.86	49.14	32.53	3.10	10.50	7.82
Run II-initial	81.91	18.09	95.87	4.13	37.84	1.67	22.74	4.00
Run II-final	61.85	38.15	46.68	53.32	23.66	1.59	14.92	7.25
Run III-initial	76.92	23.08	83.29	16.71	41.01	1.72	23.82	4.33
Run III-final	72.47	27.53	60.14	39.86	36.44	2.89	12.61	7.62
Run IV-initial	75.29	24.71	86.50	13.50	40.27	1.49	27.11	5.00
Run IV-final	65.32	34.68	59.68	40.32	23.96	2.12	11.30	8.50

The preliminary laboratory analyses results were used to calculate organic wastes' mixture ratio to fulfill the requirement for C/N = 30. The obtained ratio of food waste: yard waste was found to be 1: 0.0286 kg. The volume of each composter was 0.196 m^3. Hence, the amount of organic waste material fractions to be mixed were 114 kg and 3.5 kg for food waste and yard waste, respectively, as shown in appendix B. The aeration rate required for the stoichiometric process (Chapter II, equation 2.1 and 2.2) was found to be 0.105 L/min (0.016 m^3/d) (shown in appendix C). Due to the limited capacity of the equipment used for airflow rate measurement, the aeration rates (Q_{air}) for four runs were selected as 1.25 L/min (1.8 m^3/d), 2.5 L/min (3.6 m^3/d), 3.75 L/min (5.4 m^3/d), and 7.5 L/min (10 m^3/d) for RUN I, II, III and IV, respectively.

5.2 Temperature Profiles

The temperature profiles of each composting run were obtained by recording the temperature (°C) along with time (hours/days) measurement at each point inside the composter as shown in Figure 5.1. This figure shows the cross-section of the composter, which has a diameter of 50 cm. Points r-1 and r+1 are located at 12.5 cm from the center on both sides of the radial axis. Points r-2 and r+2 are located at the surface boundary of the composter.

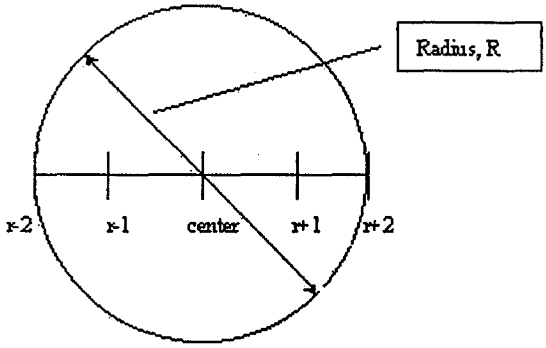


Figure 5.1 Points of temperature measurement inside the composter

Temperature profiles at the above mentioned points during the four experimental runs are shown in Figures 5.2-5.5. Temperature increased rapidly during the initial state (first few days) of the composting process and continued increasing until it had reached the maximum. The highest temperature for each experimental run occurred at the center of the composter. The maximum temperatures at other point were lower along the radial directions. That is, the temperature distributed along the radial directions from the center of the composting mass to the periphery of the composters. Thus, $T_{center} > T_{r-1}$ and $T_{r+1} > T_{r-2}$ and T_{r+2}, as the air diffused from the center throughout the composting mass to the composter's periphery. Increased temperature in the reactors indicated heat generation during the composting process. The relationship of temperature

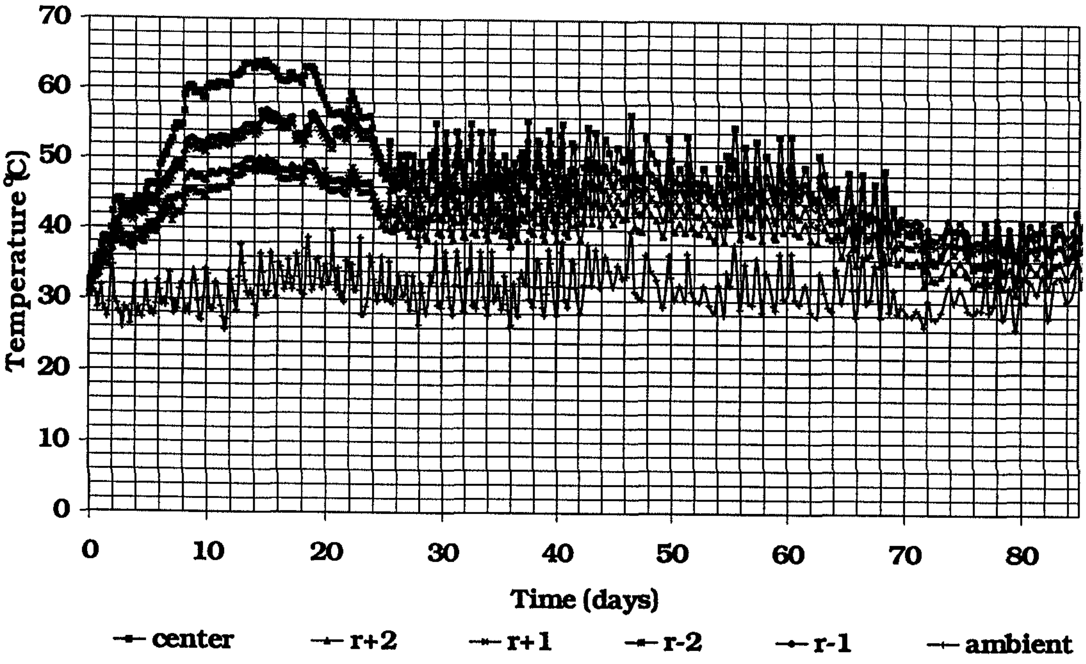


Figure 5.2 Temperature profiles for RUN I

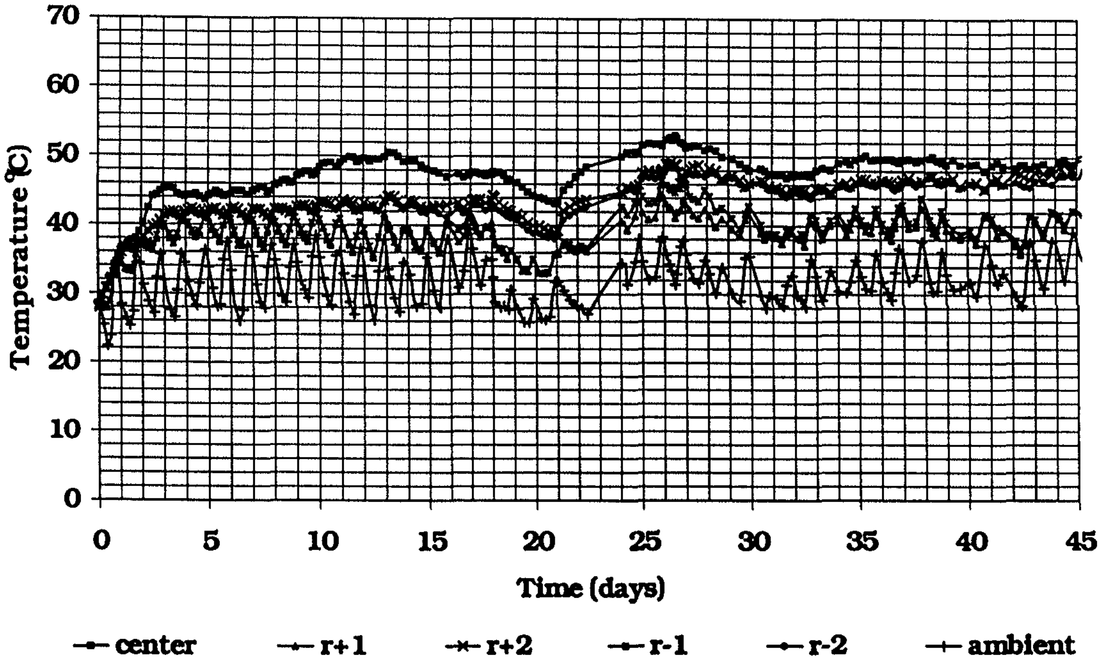


Figure 5.3 Temperature profiles for RUN II

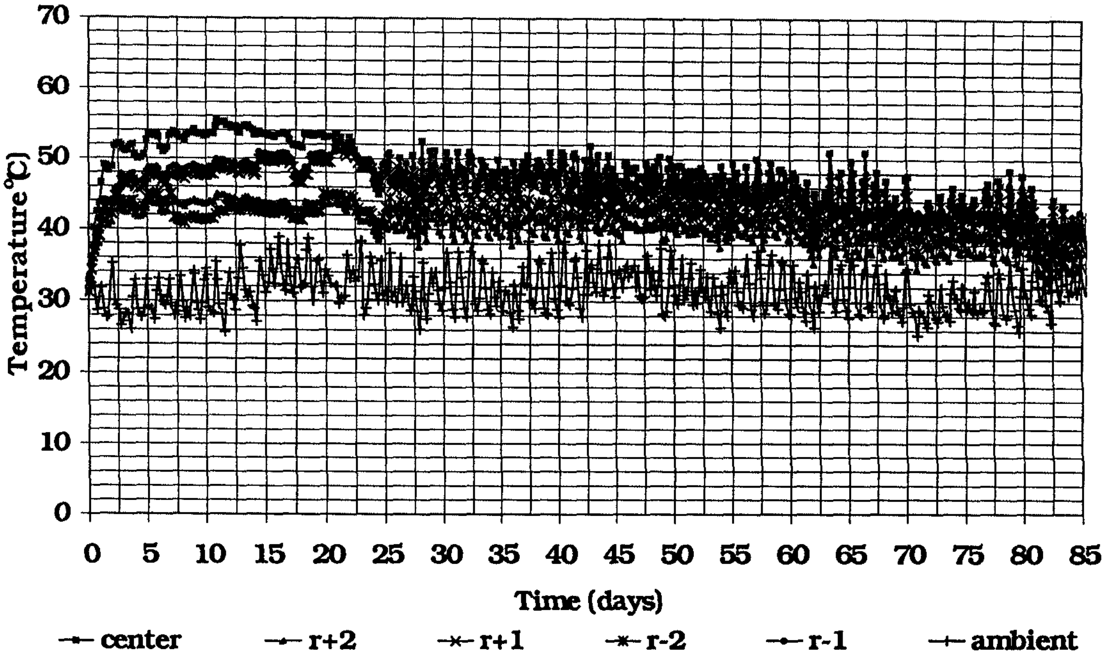


Figure 5.4 Temperature profiles for RUN III

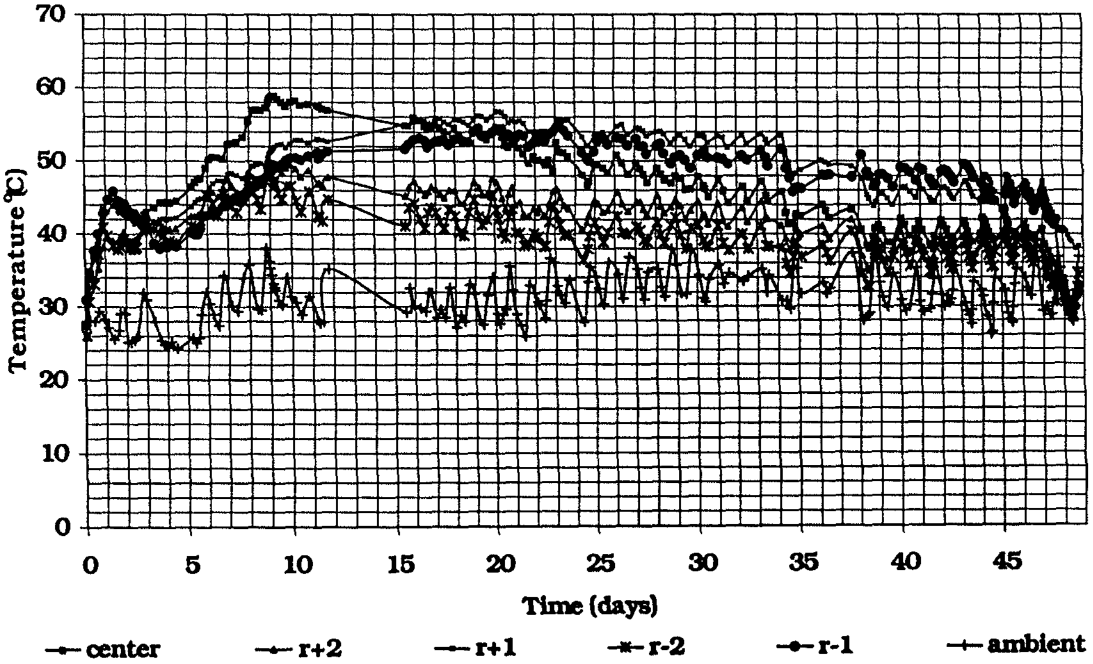


Figure 5.5 Temperature profiles for RUN IV

and time was applied to estimate heat generation rate. Aeration was a significant parameter affecting temperature distribution in composting process. Forced aeration provided from the center of the composters penetrated throughout the composting mass along radial directions. The rate of composting process is related to the amount of air available for the aerobic microorganisms. The change in temperature of the mass represents the activities of these organisms indicating organic material biodegradation. Thus, temperature distribution in the composters was dependent on the amount of air penetrating to the mass. Table 5.2 presents the initial and maximum temperatures and the time to reach the maximum temperatures of all composting runs.

Table 5.2 Initial and maximum temperatures of the four runs

Run / Q_{air}	Number of days	Average room temperature (°C)	Initial temperature (°C)	point	Maximum temperature (°C)	Time to reach maximum temperature (days)
I 1.25 L/min 1.8 m^3/day	85	31.5	31.1	center	64.0	15
				r-1	57.0	15
				r+1	57.0	15
				r-2	48.7	22
				r+2	50.0	15
II 2.50 L/min 3.6 m^3/day	45	33.1	27.8	center	51.8(a)	20(a)
				r-1	44.4(a)	18(a)
				r+1	43.2(a)	21(a)
				r-2	46.3(a)	20(a)
				r+2	46.8(a)	22(a)
III 3.75 L/min 5.4 m^3/day	85	31.5	31.1	center	55.4	11
				r-1	44.9	11
				r+1	51.4	21
				r-2	45.5	28
				r+2	52.4	21
IV 7.50 L/min 10.0 m^3/day	49	30.9	27.5	center	58.9	9
				r-1	55.3	23
				r+1	56.7	20
				r-2	48.5	9
				r+2	50.1	9

(a) The average value of 2 peaks, shown in Figure 5.3

Based on the results of temperature profiles of the four experimental runs it could be stated that, the three parameters during the composting process, aeration rate, maximum temperature, and rate of temperature change with time were interrelated. In composting process, heat conduction was distributed within and between the organisms, water gases, and compost material cells. Higher aeration rate allowed faster rate of temperature increase with time. In contrast, it allowed lower maximum temperature. Thus, it could be said that the aeration rates may be adjusted for the composting process to optimize the biodegradation rates, which are temperature dependent. Moreover, the appropriate temperature required for an aerobic composting process must be in a thermophilic range (45-75°C). This temperature range is effective for pathogen killing. Figures 5.6 and 5.7 show the correlations of the maximum temperature with the time and aeration rates, respectively.

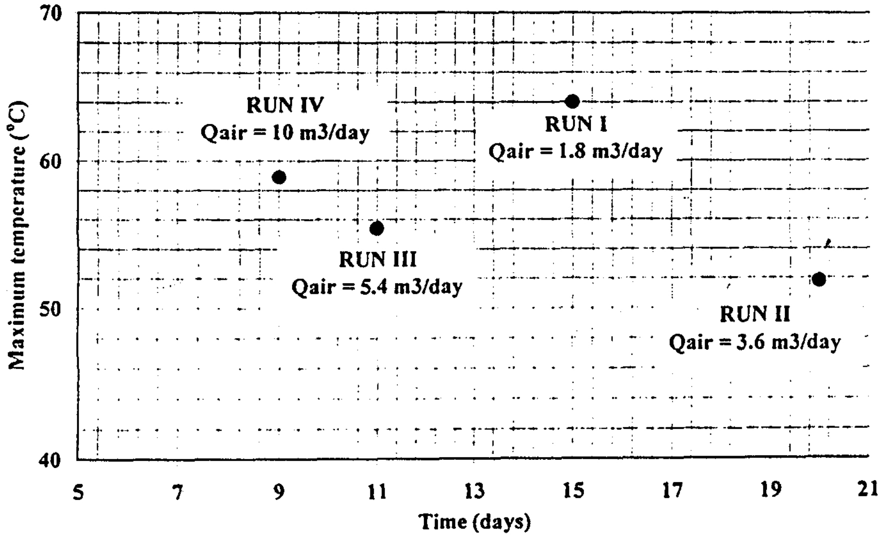


Figure 5.6 Correlation between maximum temperature and time during four composting runs

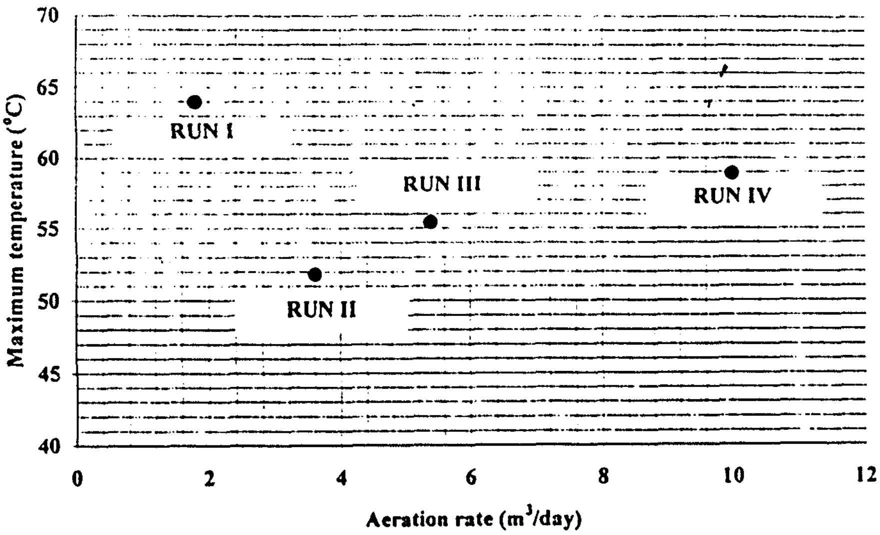


Figure 5.7 Correlation between maximum temperature and aeration rate in each experimental run

5.3 Thermal Properties of Composting Mixture

Thermal conductivity, (k): The thermal conductivity was measured using a heat probe. A voltage (V) of 3 volts applied to the heat probe produced a current (I) of 1.5 amperes. A calibration curve was obtained to calculate the effective length (L) from the slope of temperature vs. ln (time) by utilizing agar gel (slope, $m = \frac{IV}{4\pi kL}$), which has thermal conductivity, k = 0.61 watt/m/°C. The effective length of the thermal conductivity probe was found to be 0.1822 m. The experiment was conducted for four different samples of composted material with various ages (different moisture content). The results are shown in Table 5.3. Figure 5.8 shows the relationship between thermal conductivity and moisture content of the compost material.

Table 5.3 Results of thermal conductivity measurement

Sample	Sample age (days)	Room Temp. (°C)	Slope m	Thermal conductivity k (watt / m / °C)	Moisture Content (%)
Agar Gel	-	24.83	3.22	0.61	-
Sample 1	26	24.94	9.84	0.20	22.68
Sample 2	18	24.97	3.60	0.55	52.24
Sample 3	3	24.92	3.59	0.55	52.53
Sample 4	0	24.88	3.94	0.50	47.57

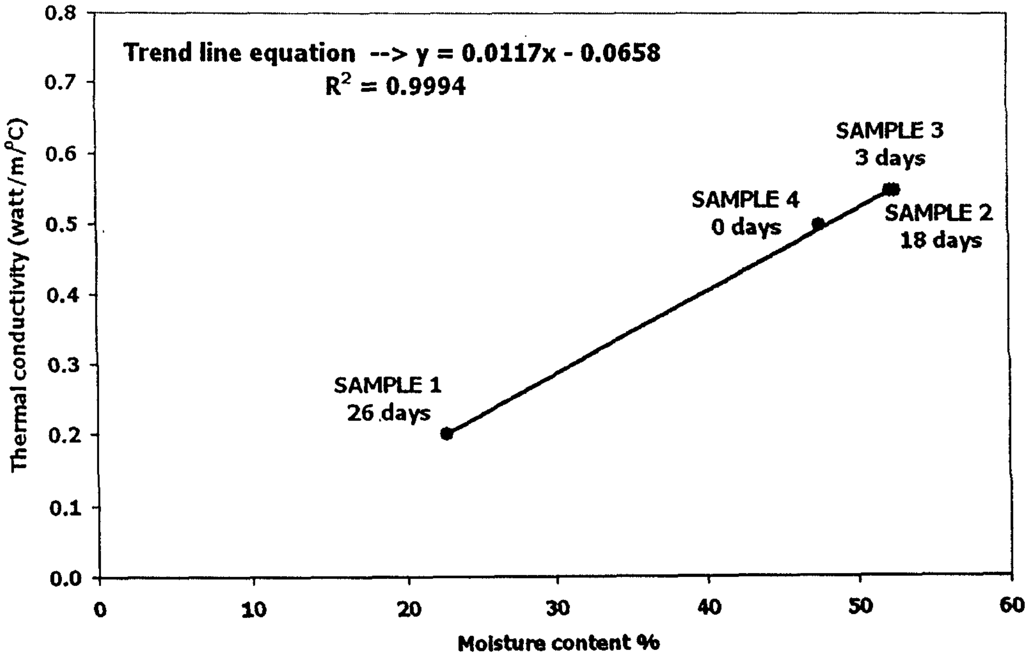


Figure 5.8 Correlation between thermal conductivity and moisture content of composted material

Moisture content of the compost material ranged broadly between 45 % - 85 %, which averaged to be 65 %. The average thermal conductivity, 0.53 watt/m/^{o}C, was used in this study.

Thermal diffusitivity, α: The thermal diffusitivity constant, α, in the unit of m^2/s can be defined as $\frac{k}{c\rho}$. The value of specific heat capacity, c, was taken to be 3.18 kJ/kg-^{o}C. Bulk density, ρ, of the waste samples, from the average of several measurements, was found to be 740 kg/m^3. Thus, the thermal diffusitivity, α, of the organic waste material used for this study was calculated to be 2×10^{-7} m^2/s.

5.4 Heat generation

Equations (3.11)-(3.13) were used in a computer program to simulate the temperature distribution of the composting mass during the biodegradation process of each run. The computer program is shown in Appendix D. Heat generated per unit volume, $\overset{o}{q}$, were assumed for each simulation run, and the rates of temperature change with time, $\frac{\partial T}{\partial t}$, were compared with the experimental ones. Correlation between the heat generation $(\overset{o}{q})$, with time (t), for each experimental run is shown in Table 5.4 and Figure 5.9.

Heat was rapidly generated during the first few days and continued increasing up to a maximum point, then decreased down to reach stable state. From this study, the maximum heat generated obtained were 133, 221.4, 242, and 483.7 W/m^3 for RUN I, II, III and IV, respectively. The highest value of the maximum heat generation $(\overset{o}{q})$, occurred in RUN IV with the highest aeration rate. The higher $\overset{o}{q}$ indicated faster rate of temperature increase with time.

Table 5.4 Heat generated during various time durations in four experimental runs

RUN I $Q_{air} = 1.8\ m^3/day$			RUN II $Q_{air} = 3.6\ m^3/day$		
Time (day)	Time (hour)	Heat generated ($watt/m^3$)	Time (day)	Time (hour)	Heat generated ($watt/m^3$)
0	0	-	0	0	-
1	24	40.6	1	24	221.4
2	48	113.1	2	48	124.0
3	72	133.0	3	72	156.3
4	96	130.7	4	96	153.3
5	120	127.2	5	120	150.0
6	144	122.2	6	144	142.5
7	168	111.2	7	168	135.1
8	192	101.9	8	192	123.4
9	216	95.8	9	216	112.7
10	240	98.1	10	240	103.4
11	264	97.0	11	264	96.4
12	288	97.5	12	288	87.2
13	312	101.4	13	312	85.0
14	336	101.1	14	336	81.6
15	360	101.3	15	360	87.4
RUN III $Q_{air} = 5.4\ m^3/day$			RUN IV $Q_{air} = 10\ m^3/day$		
0	0	-	0	0	-
1	24	59.9	1	24	483.7
2	48	185.7	2	48	109.5
3	72	236.0	3	72	190.8
4	96	242.0	4	96	210.7
5	120	235.3	5	120	208.7
6	144	216.9	6	144	181.7
7	168	206.5	7	168	164.8
8	192	191.4	8	192	145.2
9	216	178.9	9	216	132.3
10	240	168.0	10	240	128.8
11	264	155.7	11	264	124.8
12	288	147.6	12	288	122.7
13	312	140.3	13	312	125.7
14	336	135.1	14	336	124.6
15	360	129.0	15	360	121.9

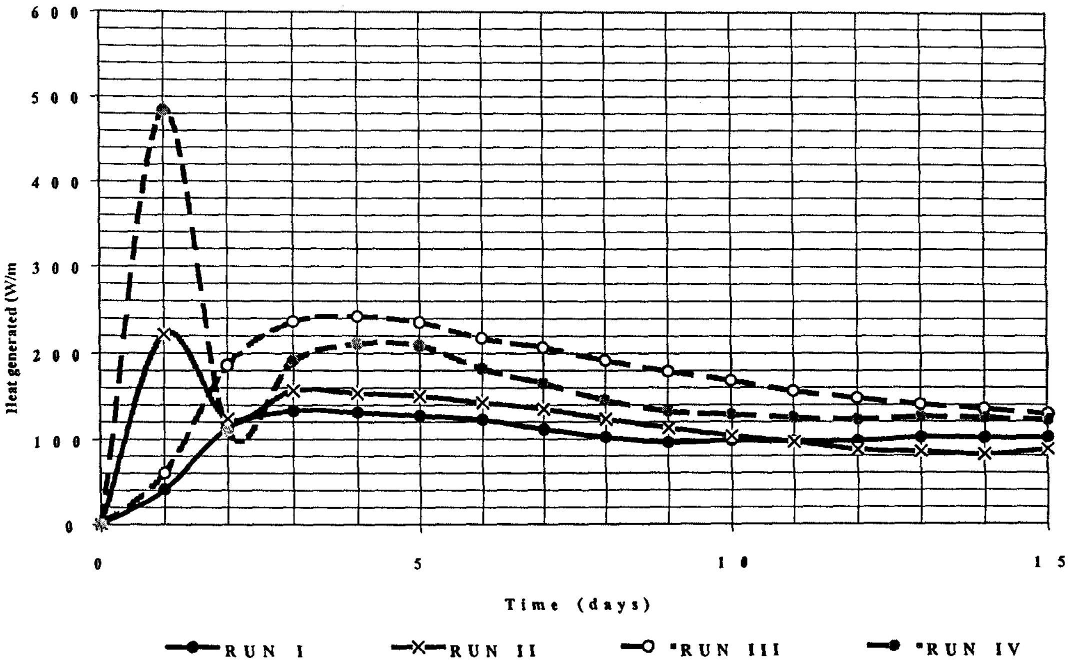


Figure 5.9 Correlation between heat generated and time during four composting runs

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Four composting runs were conducted using mixture of food waste and yard waste. The organic waste mixture ratio was 1:0.0286 by weight for food waste: yard waste. The initial C/N ratio ranged between 22-28:1, which was adequate for the biodegradation process. Four different aeration rates, 1.8 m^3/d, 3.6 m^3/d, 5.4 m^3/d, and 10 m^3/d, were used for RUN I, RUN II, RUN III, and RUN IV, respectively. Type K thermocouples and data loggers recorded temperature and time at different points inside the composters. Temperature profiles within the composting mass were monitored.

Temperatures increased rapidly at the initial state of composting process and continued increasing up to the maximum. Organic waste stabilization stage was accomplished when the temperatures decreased down to the room temperature. The maximum temperatures for all composting runs ranged between 50-64 $^{\circ}C$, which were within thermophilic range. The amount of air supplied throughout the process was an important factor for rate of temperature change with time and the maximum temperature. Temperature is an important factor affecting microorganisms growth, which carried out the biodegradation process and pathogen kills. It also indicates the stability of the compost product. Optimum air supplied for each composting process is, therefore, very necessary for composting process.

Compost product characteristics were determined after each experimental run. Decrease in organic matter and moisture content indicated the decomposition and stabilization of the organic waste. C/N ratio of the final product ranged between 11-15:1 and total volatile solids ranged between 47-60 %. The product's moisture content was still high comparing to soil and other commercial solid fertilizers.

Thermal properties were also obtained from the laboratory experiments and calculations. Organic waste samples' average thermal conductivity, k, was obtained to be 0.53 $W/m/^{o}C$ and thermal diffusivity, α, was calculated to be 2.7×10^{-7} m^2/s. One-dimensional heat balance equation was derived for cylindrical coordinate system. Explicit finite different method was used to develop numerical scheme for determining the heat generation in the composting process. Three equations for interia nodes, center node, and surface node were used in the computer program to estimate heat generated during the process. The maximum heat generated during RUN I, RUN II, RUN III, and RUN IV were 133, 221.4, 242, and 483.7 W/m^3, respectively. Aeration rate was an important factor for heat generation in the composting process.

6.2 Research Limitations

The main research objectives were to study the temperature distribution and heat generation in an aerobic composting process. Several parameters were controlled and assumed. It is realized that the condition may vary in actual practice with regard to the heat generation and dissipation during the composting process. The modified insulated reactors were designed to prohibit and mitigate heat lost to the environment due to air conduction. Therefore, heat lost throughout the process was neglected.

Although, the reactors were insulated and very much closed, the air provided to the composting process was not temperature controlled. The temperature recorded fluctuated according to the environmental temperature. The fluctuations were neglected to have clear understanding for the temperature profiles. Fluctuation also appeared in aeration rates. The air compressor collects and compresses air inside the container while providing air to the composters. Once the air pressure inside the compressor decreases to a selected point, then, the compressor automatically starts collecting air again. This fluctuation may also cause temperature to fluctuate.

Temperature did not equally distribute throughout the composting mass, thus, a uniform distribution was assumed for this study. The assumption was made based on the experimental results. Temperature differences along the radial axis were neglected.

Related to several factors, for example, climate, seasons, and cultural impact, food waste characteristics varies widely. A mixture of selected food waste was used to maintain somewhat constant initial values of its characteristic.

Effective microorganisms, known as E.M., were used for this study. Equal amount of E.M. was added to the mixed organic waste prior composting runs to ensure the aerobic conditions. Many studies had been completed mainly for effects of E.M., nevertheless, no convinced conclusion had been brought up. E.M. is believed to stimulate the biodegradation process and it is sounded for odor control. Since the equal amount was added to each experimental run, E.M. was not a factor effecting this study.

Mixed organic waste samples were assumed to be homogeneous, thus, thermal properties of the material were constant. These thermal properties were specific heat capacity, thermal conductivity, and thermal diffusivity. Likewise, samples' moisture content during the biodegradation changes in accordance to time and state of the process. From this study, thermal conductivity of the sample was clearly influenced by moisture content. However, for simplicity, the samples were assumed to be isotropic, for which the conductivity is the same in all directions and time.

6.3 Recommendations

This study concerned only one-dimensional distribution, three-dimension may be applied to explicit finite different method for better solution of heat generation. Three-dimension Cartesian and cylindrical system give different solution, and both must be applied to have a complete view of temperature distribution. A designed and engineered system must be used to prevent unnecessary cost. Energy input and output can be useful to optimize the system. This experimental setup can also be applied to any biological processes that produce heat.

Moreover, temperature distribution is significantly important for microbial growth and activities, including pathogen kills in a static unit. In a static composting unit, forced air supply to the system can be distributed for higher efficiency. Several air diffusers can be used to spread the air all through the body, nevertheless, high aeration can cause heat to escape from the system and thus the system temperature cannot reach thermophilic state. In other words, system optimization must be studied deeply.

Composting is a natural process in the ecosystem under suitable conditions. Any organic material can be biodegraded under the presence of microorganisms (aerobic and anaerobic). Considering heat generated in composting process, landfill can be a major source for biodegradation. Heat generation and temperature distribution in the landfill mass should be studied. The dangers may arise when hazardous wastes react; heat catalyzes some chemical reaction.

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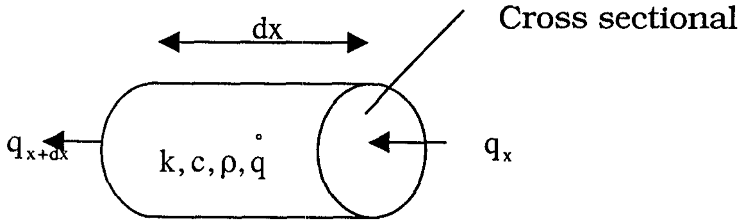
Appendix A.

Fourier's Equation

Fourier's Equation

One-dimensional heat transfer (Rao, 1999):



Heat inflow during time dt + Heat generated by internal sources during dt = Heat outflow during dt + Change in internal energy during dt

$$q_x dt + \overset{\circ}{q}\,dxdt = q_{x+dx}dt + \rho c dTdx$$

$$q_x = -kA\frac{\partial T}{\partial x}$$

$$q_{x+dx} = -kA\frac{\partial T}{\partial x} - \frac{\partial}{\partial x}\left(kA\frac{\partial T}{\partial x}\right)dx$$

$$\left(-kA\frac{\partial T}{\partial x}dt\right)+\left(\overset{\circ}{q}\,dxdtA\right)=\left[-kA\frac{\partial T}{\partial x}-\frac{\partial}{\partial x}\left(kA\frac{\partial T}{\partial x}dx\right)\right]dt+\left(c\rho dTdxA\right)$$

The constant $\alpha = \frac{k}{c\rho}$, then $c\rho = \frac{k}{\alpha}$

$$\left(-kA\frac{\partial T}{\partial x}dt\right)+\left(\overset{\circ}{q}\,dxdtA\right)=\left[-kA\frac{\partial T}{\partial x}-\frac{\partial}{\partial x}\left(kA\frac{\partial T}{\partial x}dx\right)\right]dt+\left(\frac{k}{\alpha}dTdxA\right)$$

$$\left(-kA\frac{\partial T}{\partial x}dt\right)-\left[-kA\frac{\partial T}{\partial x}-\frac{\partial}{\partial x}\left(kA\frac{\partial T}{\partial x}dx\right)\right]dt=\left(\frac{k}{\alpha}dTdxA\right)-\left(\overset{\circ}{q}\,dxdtA\right)$$

$$kA\frac{\partial T}{\partial x}\left(-dt+dt+\frac{\partial}{\partial x}dxdt\right)=A\left[\left(\frac{k}{\alpha}dTdx\right)-\left(\overset{\circ}{q}\,dxdt\right)\right]$$

$$k\frac{\partial^2 T}{\partial x^2}dxdt+\overset{\circ}{q}\,dxdt=\frac{k}{\alpha}dTdx$$

Dividing each term by $kdxdt$, we obtain

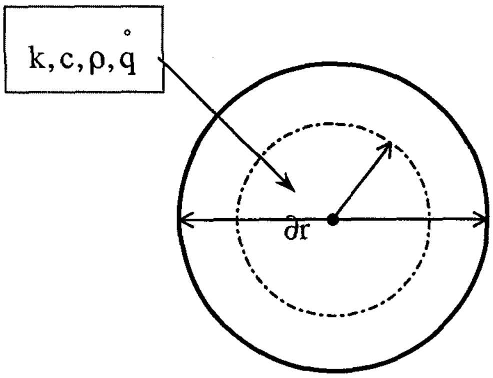
$$\frac{\partial^2 T}{\partial x^2}+\frac{\overset{\circ}{q}}{k}=\frac{1}{\alpha}\frac{\partial T}{\partial t}$$

If cylindrical coordinate system is used instead of the Cartesian system and

$$\frac{\partial^2 T}{\partial x^2}=\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)$$

$$\frac{\partial^2 T}{\partial x^2}=\frac{1}{r}\left(r\frac{\partial^2 T}{\partial r^2}+\frac{\partial r}{\partial r}\frac{\partial T}{\partial r}\right)$$

$$\frac{\partial^2 T}{\partial x^2}=\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}$$



$$\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\overset{\circ}{q}}{k}=\frac{1}{\alpha}\frac{\partial T}{\partial t}$$

Appendix B.

Composting Waste Mixture Ratio Requirement

Mixture Requirement

Determination of the quantity of yard waste needed to be mixed with this waste to rise the C/N ratio of the mixture to 20-35:1, suitable for composting.

Sample Type	Bulk density, kg/L	% solids	% moisture	% ash	% VS	% N	% C	C/N ratio
Food waste	0.740	20	80	20	80	1.78	39.22	22.03
Yard waste	0.075	50	50	20	80	1.24	40.46	35.63

Mass balance:

For 1 kg of food waste: C content $= 1 \times \frac{39.22}{100}$ kg

$= 0.3922$ kg

N content $= 1 \times \frac{1.78}{100} \times \frac{1}{22.03}$ kg

$= 8.07989 \times 10^{-4}$ kg

For x kg of yard waste: C content $= x \times \left(\frac{40.46}{100}\right)$ kg

$= 0.4046\ x$ kg

N content $= x \times \left(\frac{1.24}{100}\right)\left(\frac{35.63}{1}\right)$ kg

$= 0.441812\,x$ kg

$$\text{Therefore,} \quad \frac{C}{N} = \frac{30}{1}$$

$$\frac{30}{1} = \frac{0.3922 + 0.4046\,x}{8.07989 \times 10^{-4} + 0.441812\,x}$$

$$0.02423967 + 13.25436\,x = 0.3922 + 0.4046\,x$$

$$12.84976\,x = 0.36796033$$

$$x = 0.0286$$

$$x = 0.0286 \text{ kg of yard waste}$$

1 kg of fw requires mixing 0.0286 kg of yw to get the C/N ratio to 30:1

Total mass required:

The total volume of the composter:

$$V_{total} = \pi(r_{composter})^2(L_{composter}) - \pi(r_{pipe})^2(L_{pipe})$$

$$= \pi \times (0.25)^2 \times 1.0 - \pi \times (0.0127)^2 \times 1.0$$

$$\approx 0.196\,\text{m}^3$$

from $\rho = \dfrac{\text{mass}}{\text{volume}} = \dfrac{m}{V}; \quad V = \dfrac{m}{\rho}$

and $\dfrac{m_{fw}}{m_{yw}} = \dfrac{1}{0.0286}\dfrac{\text{kg}}{\text{kg}}; \quad m_{yw} = 0.0286\,m_{fw}$

Mass balance:

$$\begin{aligned}
V_{total} &= V_{fw} + V_{yw} \\
0.196\,\text{m}^3 &= \frac{m_{fw}}{\rho_{fw}} + \frac{m_{yw}}{\rho_{yw}} \\
&= \frac{m_{fw}}{740\,\frac{\text{kg}}{\text{m}^3}} + \frac{m_{yw}}{75\,\frac{\text{kg}}{\text{m}^3}} \\
&= \frac{m_{fw}}{740} + \frac{0.0286\,m_{fw}}{75} \\
0.196 &= \frac{75m_{fw} + 21.164\,m_{fw}}{55500} \\
10878 &= 96.164\,m_{fw} \\
m_{fw} &= 113.12\,\text{kg} \\
m_{yw} &= 3.24\,\text{kg}
\end{aligned}$$

Appendix C

Aeration Requirement Estimation

Aeration Estimation

Thermophilic reactions will require quantities of oxygen several times higher than those of mesophilic and maturation reactions. Additional amounts of air need to be supplied to compensate for loss to the atmosphere can be up to 95-99%.

Determination of the amount of oxygen required to oxidize x kg of yard waste aerobically.

Typical chemical composition of yard waste is $C_{23}H_{38}O_{17}N$

$$C_aH_bO_cN_d + \left(\frac{4a + b - 2c + 3d}{4}\right)O_2 \rightarrow aCO_2 + \left(\frac{b - 3d}{2}\right)H_2O + dNH_3$$

$$C_{23}H_{38}O_{17}N + \left(\frac{4 \times 23 + 38 - 2 \times 17 + 3 \times 1}{4}\right)O_2 \rightarrow 23CO_2 + \left(\frac{38 - 3 \times 1}{2}\right)H_2O + NH_3$$

$$C_{23}H_{38}O_{17}N + 24.75O_2 \rightarrow 23CO_2 + 17.5H_2O + NH_3$$

Molecular weight of $C_{23}H_{38}O_{17}N$ = $12 \times 23 + 1 \times 38 + 16 \times 17 + 14$

= 600 g/mol

Molecular weight of $24.75O_2$ = $24.75 \times 16 \times 2$

= 792 g/mol

1 g of $C_{23}H_{38}O_{17}N$ requires: $O_2 = \dfrac{792}{600} \approx 1.32g$

BVS = $0.830 - (0.028)X$

Where BVS = biodegradable volatile solids

X = lignin content, % of VS

X_{yw} = 4.1 % of VS (Haug, 1993)

BVS = $0.083 - (0.028) \times 4.1$

= 0.7152 = 71.25%

BVS mass of x kg yard waste:

= $x\,kg \times \%BVS$

= $xkg \times 0.8 \times \%\,VS$

= $x \times 0.0.7125 \times 0.8$

= 0.57 x kg

Air required: $$= \frac{(0.57x)\text{kgBVS}\times(1.32\times10^{-3})\frac{\text{kgO}_2}{\text{kgBVS}}}{0.23\frac{\text{kgO}_2}{\text{kgAir}}\times(1.2\times10^{-3})\frac{\text{kgAir}}{\text{L}}}$$

= (2.73 x) L of air required

Assuming an oxygen demand is 35 % for the successive days of 5-days composting period, the aeration rate will be:

$$= \frac{(2.73x)\text{L}\times\frac{0.35}{\text{day}}}{1440\frac{\text{min}}{\text{day}}}$$

$$= (6.64\times10^{-4})x\frac{\text{L}}{\text{min}};\ x = 3.24\,\text{kg}$$

$$= 2.16\times10^{-3}\ \frac{L}{\text{min}}$$

Typical chemical composition of food waste is $C_{18}H_{26}O_{10}N$

$$C_{18}H_{26}O_{10}N+\left(\frac{4\times18+26-2\times10+3\times1}{4}\right)O_2\rightarrow18CO_2+\left(\frac{18-3\times1}{2}\right)H_2O+NH_3$$

$$C_{18}H_{26}O_{10}N+20.25O_2\rightarrow18CO_2+7.5H_2O+NH_3$$

Determination of the amount of oxygen required to oxidize x kg of food waste aerobically.

Molecular weight of $C_{18}H_{26}O_{10}N = 12\times18+1\times26+16\times10+14$

$= 416$ g/mol

Molecular weight of $20.25O_2 = 20.25\times16\times2$

$= 648$ g/mol

1 g of $C_{18}H_{26}O_{10}N$ requires: $O_2=\frac{648}{416}\approx1.558g$

X_{fw} = 0.4 % of VS (Haug, 1993)

BVS = 0.083 - (0.028) $\times$ 0.4

= 0.8188 = 81.88%

BVS mass of x kg yard waste:

= x kg $\times$ %BVS

= xkg $\times$ 0.8188 $\times$ % VS

= x $\times$ 0.8188 $\times$ 0.8

= 0.66 x kg

Air required: $$= \frac{(0.66\,x)\text{kgBVS} \times (1.558 \times 10^{-3})\,\frac{\text{kgO}_2}{\text{kgBVS}}}{0.23\,\frac{\text{kgO}_2}{\text{kgAir}} \times (1.2 \times 10^{-3})\,\frac{\text{kgAir}}{\text{L}}}$$

$=$ (3.73 x) L of air required

Assuming an oxygen demand is 35 % for the successive days of 5-days composting period, the aeration rate will be:

$$= \frac{(3.73\,x)\text{L} \times \frac{0.35}{\text{day}}}{1440\,\frac{\text{min}}{\text{day}}}$$

$$= (9.07 \times 10^{-4})x\,\frac{\text{L}}{\text{min}};\ x = 113.12\ \text{kg}$$

$$= 0.1026\,\frac{L}{\text{min}}$$

Total air required

$$Q_{\text{air}_{\text{fw}}} + Q_{\text{air}_{\text{yw}}} = 0.1026 + 2.16 \times 10^{-3}\,\frac{L}{\text{min}}$$

$$\therefore Q_{a_1} = 0.10476\,\frac{L}{\text{min}}$$ for actual requirement

Appendix D

Computer Program

Computer program

```
10    REM: TRANSIENT HEAT CONDUCTION IN A CYLINDER WITH INTERNAL
      HEAT GENERATION BY EXPLICIT METHOD
20    REM: CONVECTION BOUNDARY CONDITIONS ARE ASSUMED
30    REM: UNIFORM INITIAL TEMPERATURE WITH CONSTANT CONVECTION
      BOUNDARY CONDNS
40    DIM T ( 1000 ) , TT( 1000 ) , R( 50 ) ,TEXP( 1000 ) , TEST( 1000 )
50    RADIUS = .5  : REM: CYLINDER RADIUS ( m )
60    H=5 : REM: SURFACE HEAT TRANSFER COEFFICIENT ( W/M^2 deg C )
70    TAIR=30!  : REM: SURROUNDING FLUID TEMPERATURE ( deg c )
80    COND=.55 : REM: THERMAL CONDUCTIVITY OF SLAB ( W/m^2.degC )
90    ALPHA=1.7/1E+07: REM: THERMAL DIFFUSIVITY ( m^2/s )
100   TIN=27.38 :REM: UNIFORM INITIAL TEMPERATURE DISTRIBUTION
110   INPUT "Internal heat generation ( W/m^3 ) =";HEAT
120   INPUT "Number of space increments ( any even or odd number )";N
125   LPRINT "Internal Heat Generation ( W/m^3 ):";HEAT
130   FGRID=.25  :  REM: FGRID is assumed to be 0.25 for stability.
140   DELX=RADIUS/N
150   DELT = ( DELX*DELX*FGRID ) /ALPHA
160   N1=N+1  : REM: NO. OF NODAL POINTS
170   FOR I = 1 TO N1 : REM: INITIALIZE R( I ) AND T( I ) VALUES
180   R( I ) = DELX*( I-1 )  :REM: RADIAL DISTANCE OF NODE I FROM CENTER
190   T( I ) = TIN
200   NEXT I
210   LPRINT:LPRINT "Time ( h )  Temp ( est )   Temp ( exp )  Error"
220   SUM=0
230   J = 1 : REM: FIRST TIME INCREMENT
240   FOR I = 1 TO N1 STEP N
250   IF I>1 GOTO 270
260   TT( I ) = 4*FGRID*T( I+1 )+( 1-4*FGRID )*T( I )+( FGRID*DELX*DELX*HEAT )
      /COND : GOTO 280
270   TT ( N1 ) = ( T( N )+H*DELX*TAIR/COND + ( DELX*DELX*HEAT*.5/COND ) ) /
      (1+H*DELX/COND)
280   NEXT I
290   FOR I = 2 TO N
300   TT( I ) = ( FGRID/2 ) * ( (2+DELX/R( I ) ) *T( I+1 )+( 2-DELX/R( I ) )*T( I-1 )+(
      2/FGRID-4 )*T( I )+(2*DELX*DELX*HEAT/COND ) )
310   NEXT I
320   TIME = J*DELT/ (3600)  'Time in hours.
330   TEXP ( J ) = -.0012*TIME*TIME+.3075*TIME+28.99
340   TEST ( J ) =T( 1 )
350   SUM=SUM+(TEXP( J ) –TEST( J ) ) ^2
360   DIFF = SUM^ .5
370   LPRINT TIME ,T( 1 ) ,TEMP( J ) ,DIFF
380   FOR I=1  TO N1
390   T( I ) =TT( I )
400   NEXT I
410   J=J+1
420   IF J>60 GOTO 440 : REM: NUMBER OF TIME STEPS (DELT)
430   GOTO 240
440   END
```

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